Nanometer X-ray Lithography

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ABSTRACT

New developments for X-ray nanomachining include pattern transfer onto non-planar surfaces coated with electrodeposited resists using synchrotron radiation X-rays through extremely high-resolution masks made by chemically assisted focused ion beam lithography.

Standard Ultraviolet (UV) photolithographic processes cannot maintain sub-micron definitions over large variation in feature topography. The ability of X-ray printing to pattern thin or thick layers of photoresist with high resolution on non-planar surfaces of large and complex topographies with limited diffraction and scattering effects and no substrate reflection is known and can be exploited for patterning microsystems with non-planar 3-D geometries as well as multisided and multilayered substrates.

Thin conformal coatings of electro-deposited positive and negative tone photoresists have been shown to be X-ray sensitive and accommodate sub-micron pattern transfer over surfaces of extreme topographical variations (over 100 microns). Chemically assisted focused ion beam selective anisotropic erosion was used to fabricate X-ray masks directly. Masks with feature sizes less than 20 nm through 7 microns of gold (aspect ratio ~ 350) were made on bulk silicon substrates and X-ray mask membranes. The technique is also applicable to other high density materials.

Such masks enable the primary and secondary patterning and/or 3D machining of Nano-Electro-Mechanical Systems (NEMS)s over large depths or complex relief and the patterning of large surface areas with sub-optically dimensioned features.

Keywords: X-rays, lithography on non-planar surfaces, conformal coating, large depth-of-field, nanolithography

1. INTRODUCTION

UV optical lithography[1,2] is the mainstream approach for patterning planar surfaces in both the IC and MEMS industries. The contemporary push towards faster and denser VLSI devices is characterized by a constant reduction in design feature size and hence the move to shorter wavelengths in projection reduction steppers in the optical deep-UV range [e.g. 248 nm (KrF), 193 nm (ArF)] where the shortest wavelengths are limited by the transmissive absorption of lens materials. In Extreme Ultraviolet (EUV) lithography[3], using wavelengths at 13.4 or 11.2 nm, elaborate schemes use reduction reflective optics coated with multilayer (Mo-Si or Mo-Be respectively) for printing. However, as the Critical Dimensions (CD) of feature sizes decrease depth-of-focus limitations of optical systems[4] are exacerbated for optical lithography necessitating extreme flatness and thickness tolerances for wafers.

There is a growing need to pattern over complex topographies resulting, for example, from the multitude of levels used in the fabrication of electronic chips, the integration of various components in optoelectronics, packaging[5] and interconnection issues (e.g. mesa definition), or the various non-planar surfaces encountered in bulk and surface machined microsystems[6],

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MEMS and MOMS. The constant reduction in feature size in IC technology and the need for higher density MEMS systems drives the development of advanced lithographic techniques and processes for the backend packaging and interconnect technologies. The resulting varying topology can be very challenging for fine line lithography and approaches to have UV accommodate any depth are complex. Several methods under development are multilayered or thick single-coat novalak[7] or epoxy[8] based resist, or the use of multiple focal plane exposures. Our approach is very different in the sense that we use a lithographic technique that is known for its wide depth-of-field and process latitude and we use thin resist coatings that conform to the topographical variations of the surface. The lithographic system elements required to meet our needs consists of a means of coating a non-planar surface with an imaging layer (high resolution resist), a high resolution mask, and a suitable lithographic mean of high resolution pattern transfer from mask to substrate over a high-depth-of-field/focus. The smaller the resolution (i.e. nanometric) the tighter the constraints and the more demanding the task.

There are not many parallel lithographic techniques simultaneously allowing for a large-depth-of-field/focus and nanometer resolution[9]. X-ray[10] and ion beam lithographic techniques provide both. Little work has been done to exploit depth-of-focus in high resolution X-ray lithography[11,12] (around 1keV) but efforts have concentrated on obtaining nanometic resolution features in thin resists on flat surfaces. On the other hand for years the depth-of-field factor has been exploited for depth X-ray lithography in the LIthographic, Galvanoformung, Abformung (LIGA- German acronym for lithography, electroplating and molding)[13] process where the high resolution patterning of thick photoresist coatings is performed by one-to-one shadow printing with higher energy X-rays (2-6 keV and recently even higher energy) collimated radiation beam which provides accurate pattern transfer over the large depth-of-field of the thick resist layer that enables the fabrication of pseudo-3D microstructures. There are also examples of pattern transfer on substrates presenting a variation of topography when the substrates have been previously patterned with other techniques (e.g. sacrificial layer for moving parts or molded microstructures).

One-to-one shadow printing with collimated X-rays provides parallel pattern transfer with enhanced resolution and vertical walls over a large depth-of-field from a mask into thin and thicker resist layers. It is a lithographic technique well adapted to provide the necessary depth-of-field and allows for patterning on a variety of substrate topographies with high resolution while simplifying the process, allowing for exposure latitude, process robustness and maintaining good line width control.

In this paper, our efforts relate to the high resolution shadow X-ray printing over large depth-of-field with collimated X-rays of the one-to-one parallel high resolution pattern transfer into a thin photoresist layer covering the surface of a topographically variant substrate. Moreover, we are reducing the feature resolution of X-ray mask patterns from microns to tens of nanometers and undertaking the printing of these patterns over large depth-of-field with collimated X-rays. We will discuss the direct manufacturing of devices with complex topographies down to nanometer features using synchrotron radiation X-ray printing from X-ray masks formed by focused ion beam enhanced etching onto thin electrodeposited conformal resist coatings. NASA's incentives for undertaking this collaborative work are discussed along with examples of applications in imaging and spectrometry.

2. HIGH RESOLUTION LITHOGRAPHY WITH LARGE DEPTH-OF-FIELD

Conventional Ultraviolet (UV) illuminated photolithographic processes for the precise (sub-micron) patterning of micro-electronic and micro-mechanical features is limited in accommodating variations in surface topography of greater than tens of microns. It is particularly impeded by diffraction and/or depth-of-focus in its capability to image small features over large variations in topography, typically at least several microns for 500 micron height variation. The main advantage of X-ray printing is the high resolution afforded by the low diffraction effects of short wavelength radiation. Additionally X-rays exhibit only limited scattering of photoelectrons and secondary electrons, and are not reflected by discontinuities in resist or from surface features. Well collimated X-ray synchrotron radiation provides further enhancement to proximity printing due to the negligibly small geometric effects resulting from very large source to mask distances (tens of meters).

The 0.5 to 0.18 micron high resolution advantage in step and repeat proximity printing has been largely exploited in the semiconductor industry using broad-band synchrotron radiation with an X-ray spectrum of around a nanometer wavelength[12]. For over twenty five years this standard X-ray proximity printing has been use in the research and development of both of Si-based and GaAs-based devices for VLSI electronics and optoelectronics. More recently it has demonstrated its capability in the manufacturing environment for critical levels of ultra-large-scale integrated (gigascale) electronics and processors. Over the last decade these techniques have also been used for exploring quantum-effects in nanoelectronics, developing nanodevices and in producing high-resolution diffractive optics with feature sizes from hundreds to a few tens of nanometers[14].

Contemporary micromachining techniques for MEMS are pushing lithography limits for aspect ratio as well as feature size and tolerances. Multi-layered surface micromachined structures can exhibit up to 10 μm of topology variation by end of process compared with less than a micron for advanced (bulk machined) electronic processes. Figure 1 presents examples of large topology variations (~7.5 micron) in micromachined ratchet and hinge structures fabricated in the Sandia SUMMiT 4-layer polysilicon surface micromaching process[15]. The depth-of-focus required for patterning to one micron design rules of the SUMMiT process is at the limit of UV lithography. These examples illustrate the topological diversity of multi-layered structures and provide examples of the surfaces that would need coating with photoresist.

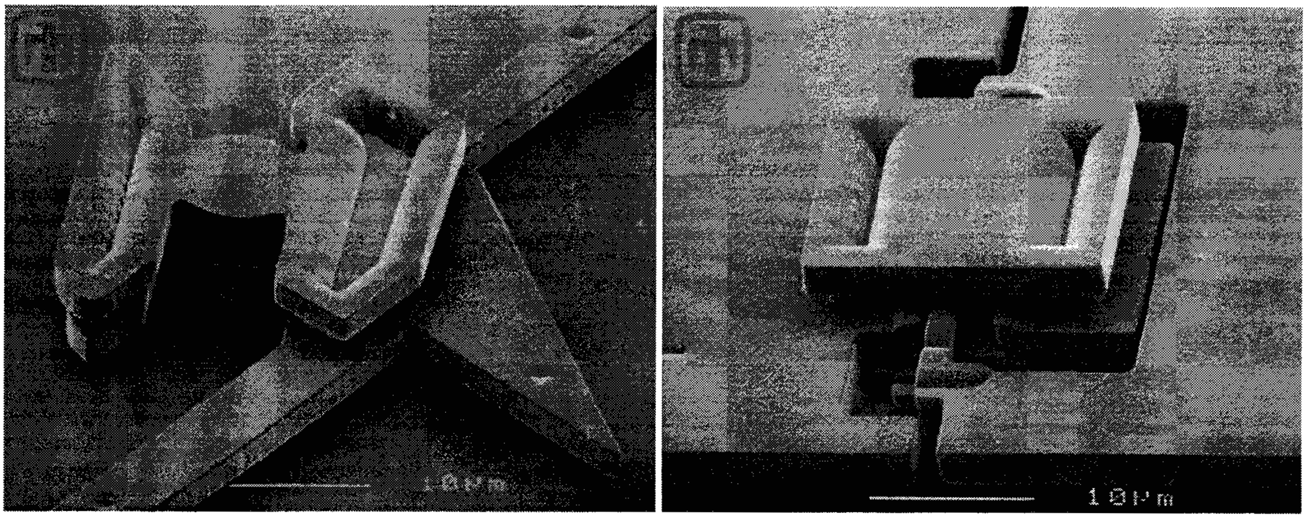

Figure 1 Examples of 7.5 micron topology variations in SUMMiT machined ratchet and hinge structures

The X-ray advantages of high depth-of-field and power to penetrate through a single layer of thick photoresist have been exploited in depth X-ray lithography for high-aspect-ratio MEMS-related applications using a LIGA type process. Here the X-rays are used to form high-aspect-ratio resist microstructures with thickness from fractions to tens of millimeters. Figure 2 presents some examples of high-aspect-ratio electroformed structures obtained by depth X-ray lithography at the Center for Advanced Microstructures and Devices (CAMD) at Louisiana State University.

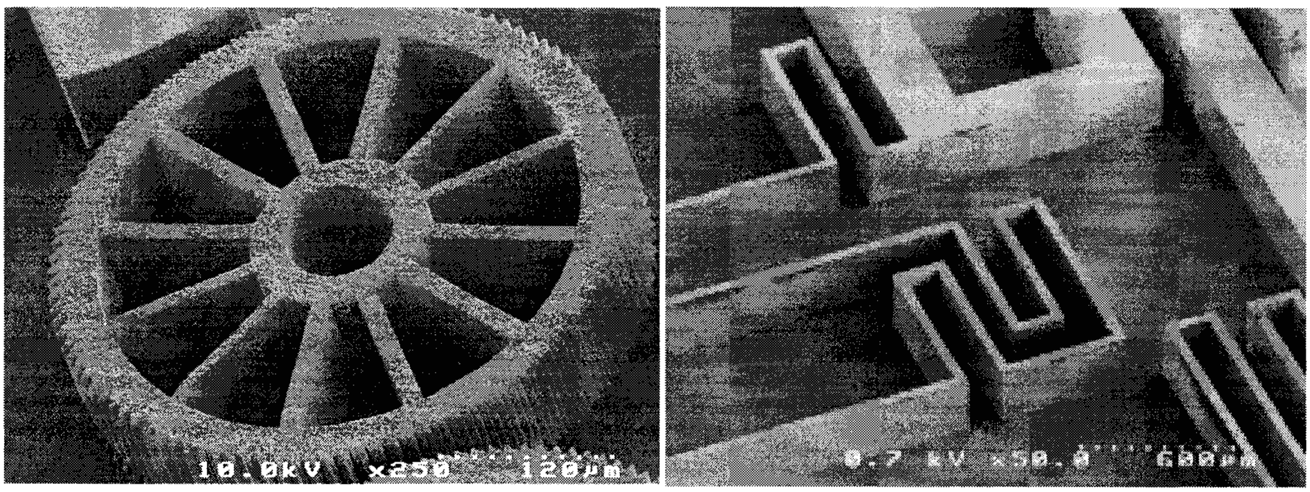

Figure 2. Examples of Deep X-ray Patterning at CAMD

At short wavelength, even at the wavelengths (λ) of hard X-rays, in the order of few tenths of nanometers, diffraction effects cannot be entirely neglected when extremely high resolution is required over very large mask-to-wafer gap values (g) of hundreds of microns [minimum linewidth due to Fresnel diffraction in proximity printing defined approximately as $0.5(\lambda g)^{1/2}$][16]. This is also true when very large topography is present, resulting in very large gaps. While depth X-ray lithography is traditionally used to accurately pattern through thick layers of resist (millimeters) over flat surfaces, it is used in our applications to accurately pattern thin resist coatings over large topological variant surfaces, over multilayered surfaces or multisurfaces simultaneously.

3. CONFORMAL ELECTRODEPOSITED RESIST ON NON PLANAR SURFACES

Large topologically variant surfaces present another problem, that of applying thin uniform coatings of photoresist. Traditional screen-printed, roller-coated or spin-coated (thinner peripherally due to greater centripetal forces) resists do not provide uniform thickness even over flat surfaces. Over uneven and extremely diverse topological surfaces, centrifugally-spun resists streak, fill deep crevices and miss elevated mesas.

Electroplating is the most straightforward method of depositing thin photoresist films uniformly over geometrically complex and topographically diverse conductive surfaces. It also generates less substrate stress (little intrinsic stress in deposits) and can accommodate a wide variety of substrate sizes and shapes that are determined by the plating bath geometry. Conformal coatings of electrodeposited resist cover every exposed surface, fill surface irregularities, cover both sides of a substrate or membrane and the surfaces of any voids or holes. Precise X-ray shadow image exposures will be cast simultaneously on all resist in path. Thus precision alignment marks could be patterned on both sides of a wafer, for subsequent alignment of micro machining masks in double-sided wafer processing, or precision patterns imaged down the walls of vias enabling the placement of multiple circuits through a single hole (i.e. facilitating ultra dense circuitry). Also exposure of folded resist covered foil or flexible membranes will define a pattern on each layer of resist enabling the elaborate patterning of flexible circuit wiring networks or the patterning of wiring circuits on complex 'origami' folded medium.

Electrophoretic photoresist depositions are a self-limiting process where only a certain thickness of electro-coating can be deposited before the insulating nature of polymer prevents further deposition. Emulsions of cathodic (or anodic) micelles are neutralized and deposit internal monomer, dye and photo initiators onto the conducting surface of exposed electrodes. Shipley Company Inc. (SCI) produces both positive and negative resists for UV exposure[17]. Their positive working water-borne resist is the PEPR 2400, which is applied by direct current anodic electro-deposition where the charged resist component micelles migrate to, and are uniformly deposited upon, an electrically conductive substrate. Their negative working aqueous emulsion resist is the Eagle 2100 ED, which is applied by direct current cataphoretical electro-deposition of the charged resist components onto an electrically conductive substrate. The conformal depositions may take place over extremely diverse surfaces and uniformly coat all surfaces of conducting substrate or conducting surface coatings, including through any substrate perforations.

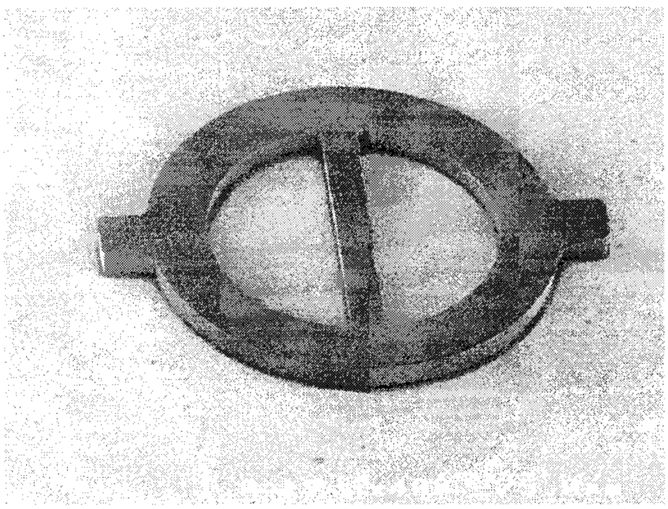

Figure 3. X-ray lithography of Eagle 2100 ED resist on smooth sputtered copper coated silicon wafer exposed on XRLC1 beamline.

We have established that both the positive and negative electrodeposited resists provide a conformal deposition over a smooth flat surface of a metal-covered polished silicon wafer (Figure 3) and over the rough surface of metal-coated fiber glass (Figure 4)[18]. SCI developed these resists for single-pass conveyor-belt type processing of circuit boards. Both photoresists are insensitive to yellow light and have their peak photosensitivity over the 380-420 nm and the 340-400 nm bandwidths for the positive and the negative tone resists respectively.

4. X-RAY PRINTING OF ELECTRODEPOSITED RESIST

Shadow printing using X-rays from the Center for Advanced Microstructures and Devices (CAMD) synchrotron radiation light source was used to pattern thin layers of both electrodeposited photoresist on XRLC1 and XRLM3 beamlines to establish their respective X-ray sensitivities. The XRLC1 beamline is optimized for high resolution IC printing with standard X-ray lithography in thin resists (< 10 μm). Its transmitted spectrum is broad-band in the 7Å-14Å range with an integrated power density of 68 mW/horizontal-cm with the storage ring operating at 1.3 GeV electron energy and 100 mA electron beam current. The XRLM3 beamline has a harder energy spectrum and is used for deep X-ray lithography of high-aspect-ratio MEMS structures with a spectrum in the 1.5 Å - 6 Å range with an integrated power density of 415 mW/ horizontal-cm with the storage ring operating at 1.3 GeV electron energy and 100 mA beam current[19].

Wafers/substrates were scanned vertically through the beam with the X-ray dose calculated by integrating the storage ring current over time. MCNC* LIGA X-ray masks were employed. Both the Eagle 2100 ED negative resist and the PEPR 2400 positive resist were found to be sensitive to X-rays with Eagle 2100 ED resist requiring 120-150 times the dose (400mJ/cm^2) required at its peak UV (340-400 nm) sensitivity and the PEPR 2400 resist requiring even higher proportional dose. Figure 3 shows electron microscope enlargements of developed images of the small featured parts of the printed test pattern attesting to the suitability of this Eagle 2100 ED negative working photoresist for thin film (5 µm) for hard X-ray lithography. Again clear, clean and high contrast images were obtained for PEPR 2400 as illustrated in Figure 4.

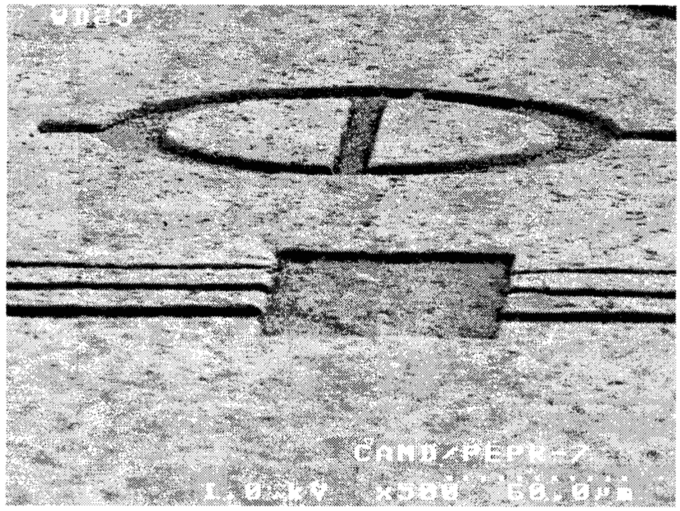

Figure 4. X-ray lithography of 5 micron thick PEPR 2400 exposed on XRLC1 beamline.

Electro-deposited resist of 7-8 micron thickness was also applied to copper coated fiber glass circuit boards and through-hole plated vias to provide a structure of extreme topological variation. In this trial a higher absorber thickness (10-microns of gold) and linear test pattern mask was used. Figure 5 demonstrates the clarity of pattern projection through the conformal thin resist (8µm) PEPR-2400 positive tone photoresist from a non-planar surface down into a via cavity that represents a depth-of-field in excess of 100 micrometers. Despite the roughness of the copper coated substrate, and subsequently the roughness of the surface of the resist, this exposure represented a most encouraging demonstration of large depth-of-field lithography afforded by X-rays. Indeed the patterning depth was limited by copper ridge shadowing, not any diffraction constraints.

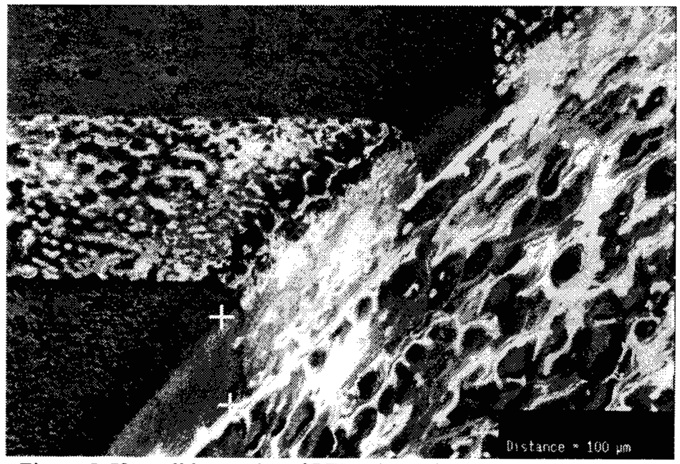

Figure 5. X-ray lithography of PEPR 2400 down a via 100 µm deep on rough copper exposed on XRLM3 beamline.

This work clearly established that electrodeposited photoresists can be patterned with X-rays over large variations of topography or depth-of-field that exceeds 100 micrometers.

5. NANOMETER X-RAY MASKS PRODUCED BY FOCUSED ION BEAM ENHANCED ETCHING

The finesse of a mask pattern is the principal feature in any one-to-one parallel lithographic method as it contains the geometrical information to be printed. Nanometer feature size lithography represents a major paradigm shift for the electronics and micro-electro-mechanical industries.

An X-ray mask is generally of a composite structure consisting of a substrate of low Z material which acts as a mechanical support (membrane or bulk material) for X-ray absorbing microstructures of high Z-material (gold, tungsten, tantalum, etc.) while being X-ray transmissive at the wavelength of interest. Depending upon the energy of the X-rays and the height of resist microstructures that need to be produced, the thickness of the mask absorber varies between a few tenths of micrometers for microelectronic applications to tens of micrometers for stacked simultaneous exposures and the very thick resist layers of the LIGA process using very hard X-rays[20]. In the conventional processes for the fabrication/manufacture of LIGA masks[21], gold absorber microstructures are electroplated after the pattern has been defined in a multi-step lithographic process:

* http://mems.mcnc.org and http://mems.mcnc.org/Hiclick.htm

- for low-to-medium resolution masks by UV proximity photolithography from a UV mask
- for high resolution masks, by X-ray copying from a lower contrast intermediate X-ray mask, the UV and first X-ray masks generally being patterned by electron beam lithography.

Current electron-beam pattern generators provide sufficient CD control and overlay for submicron to nanometer feature, especially on membranes where the proximity effect is minimized. There is however a considerable effort underway to find rapid and low-cost fabrication methods for producing masks for the fast prototyping of microdevices.

The chemically enhanced FIB technique allows for highly selective anisotropic and rapid erosion of thick high Z absorbers. It has been used in the direct manufacture of X-ray masks, with sub-optical critical dimension, allowing for considerable simplification of the structuration process and faster turn-around time[22]. The technique is a means for the fast prototyping of high-resolution X-ray masks. The direct writing and etching of the absorber pattern is done in one single step, considerably simplifying the whole fabrication process. In this presentation, we discuss the capability of focused ion beam enhanced etching systems to manufacture X-ray masks with high-aspect ratio absorber features of nanometric size that are suitable for deep X-ray lithography. In particular, the technique allows for selective highly anisotropic erosion of thick gold, or other high Z materials, coatings with unprecedented advantages:

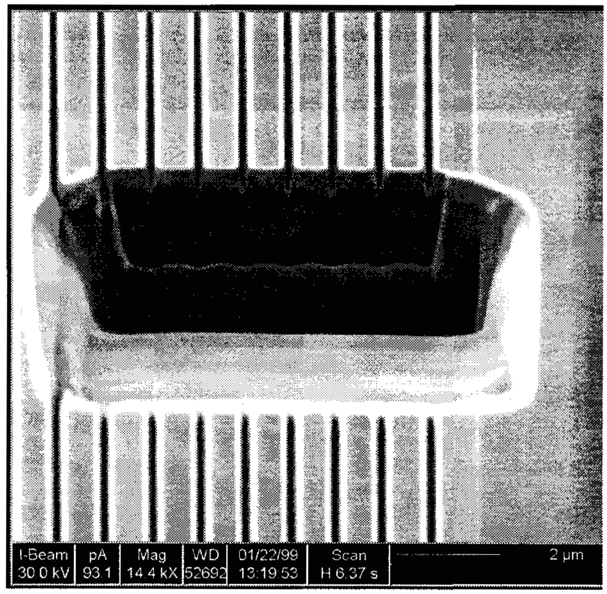

Figure 6. Grating of ~20 nm width lines milled directly in 3.5µm of Au (hole FIB cut through 200µm silicon substrate).

- Simplification of process where patterns are etched directly without intermediate imaging layer
- Wide range of sizes from nanometer wide to multi-micron wide size structures encompassing lateral feature sizes with several orders of dimensional magnitude (from nanoworld to MEMS's tens of micrometers)
- High removal rates of thickness from a few tens of nanometers to tens of micrometers by using a reactive atmosphere
- Very high aspect ratios (hundreds)
- Very good pattern definition and accuracy
- Steep and smooth walls obtained with small ion beam currents

The FEI system used in this work was equipped with a Gallium liquid metal ion source operating at 30 keV. In preliminary demonstrations of this fabrication technique at Norsam Technologies*, 22 nm width lines were milled directly through 0.9 micron of gold in an automated Gallium ion assisted FIB system. To increase the milling rate and verticality of walls and to avoid redeposition of sputtered materials during the process, reactive iodine gas was also injected into the ion beam by a small diameter needle positioned close to the sample surface. The addition of the iodine increased the milling rate of the gold by at least a factor of 10 (as is typical of other metals). For example, the 20 nm wide x 400-micron long x 3.5 micron deep trenches in gold absorber (Figure 6) required 1.8 s without iodine and in 0.07 s with iodine. In Figure 7 an even larger magnification (40K) image of portion of a zone plate is presented where the outer rings again demonstrate a CD of 20 nanometers. A mass quadrupole X-ray mask was scaled down dramatically and chemically enhanced FIB was used to mill the pattern directly through 7 microns of gold. Figure 8 represents an ion beam micrograph of this mask that demonstrates a CD of a few tens of nanometers at the quadrupoles (center apertures) and an aspect ratio of 350.

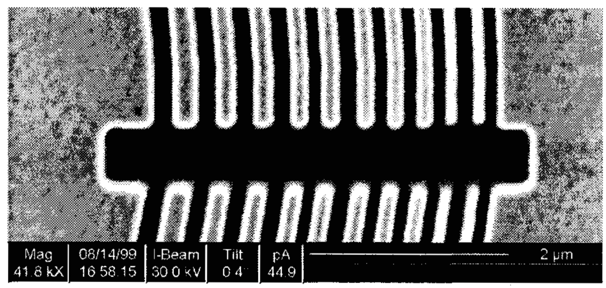

Figure 7. Zone plate rings milled directly in Au

The chemically assisted focused ion beam etching of X-ray masks with CD of 20 nm and aspect ratios of several hundreds represent an initial effort. Refinements of the technique are expected to reduce CD by a further factor of three (to ~7 nm) and increase aspect ratios by a factor of three. Assuming that electronic circuits and/or micro-devices scale proportionally, the

* http://norsam.com

surface area of devices processed with X-ray lithography and 20 nm CD X-ray masks would be 0.5% that of contemporary devices (350 nm CD). A 7 nm CD capability would represent a further order-of-magnitude reduction in die area.

Chemically assisted focused ion beam machining, not withstanding its exquisitely small CD, represents a dramatic simplification of the conventional mask making process with a much faster turn-around time and a wide diversity of applications. The direct FIB etching of X-ray masks with nanometer CD enables the X-ray printing of LIGA thick resist molds with sub-micron CD or the X-ray printing in thin resist on surfaces with large variations in topology (large depth-of-field) with nanometer CD. FIB can also be extended to the creation of more complex masks such as the fabrication of "grey-scale" masks. Here topographical variations in the absorber layer on the mask can be amplified by X-ray pattern transfer printing to provide non-planar patterning of the substrate[23].

6. APPLICATIONS OF NANOMETER X-RAY LITHOGRAPHY ON NON-PLANAR SURFACES

The lithographic system, combination of large-depth-of-field X-ray printing with conformal thin resist coating on a non-planar surface, essentially represents a 3D patterning capability. The capability of creating X-ray shadow masks of nanometer CD enables the fabrication of sub-optical features over large area curved surfaces. Another patterning advantage of this technique, that is unique due to the properties of collimated X-rays, is maintaining sub-micron feature definition simultaneously over both sides of a substrate, through perforations in a substrate and simultaneously on every surface of a folded flexible medium. In addition fabrication of X-ray masks with this technique has application in the fabrication of other X-ray components such as high resolution apertures, gratings, and zone plates for the synchrotron radiation or plasma diagnostics community. Other applications for this technology are in the nanomanufacturing of electronics components and of a variety of nanosystems that have complex topography.

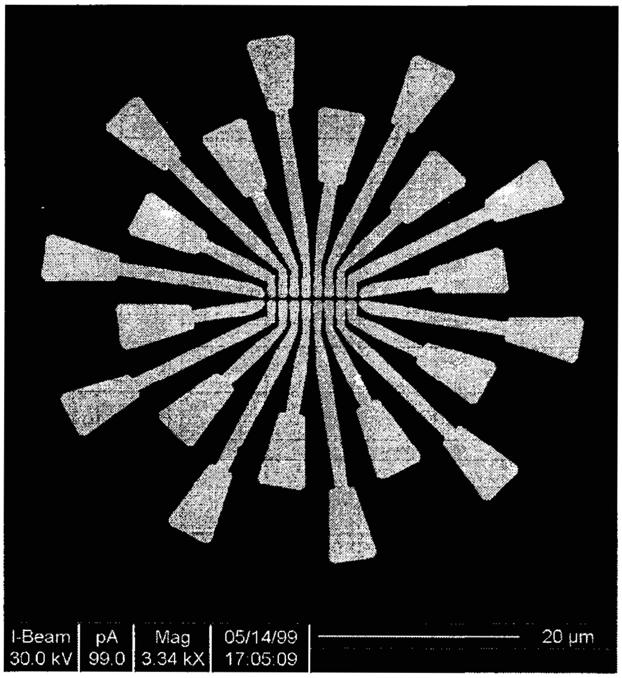

Figure 8. Etched pattern demonstrating a CD < 20nm milled directly in 7 μm of electroplated Au

NASA can no longer afford to build the large $ Billion multi-ton spacecraft, to acquire the huge launch vehicles to put them in orbit or the decade or more of solar system gravity assists to reach a destination planet. Smaller, lower mass, lower cost, more reliable and superior performance spacecraft, landers, penetrators and instruments are required. Generally an order-of-magnitude improvement in a particular attribute is meritorious, but in this research we will demonstrate how more than two orders-of-magnitude improvements in volume and mass and an order-of-magnitude improvement in performance can be realized by capitalizing on depth-of-field. Smaller critical dimensions afford further significant and more pervasive improvements – examples of this will also be discussed below.

6.1 Imaging and Navigation Systems

The creation of curved detectors is not currently a popular concept as silicon crystal planes are naturally flat, detector arrays are hard enough to make already, and conventional printing cannot provide sub-micron critical dimensions over the required depth-of-field. But the use of curved detectors in image systems greatly simplifies instrument design, improves performance and reduces cost. The human eye provides a natural example where the lens, together with the cornea, form a curved (nearly spherical) focal surface that is strongly concave toward the lens, coinciding with the curved shape of the retinal surface at the back of the eye. In the evolution of eyes, Nature has taken advantage of the simplicity that is made possible when the focal surface of an imager is curved and nearly concentric to the lens.

The simplification derives from the principle that an imager having spherical symmetry has no axis of symmetry, and therefore exhibits no off-axis aberrations. The aberrations we are usually most concerned about are coma, astigmatism, and, generally the most important, defocus. The complexity and cost of an imager (such as a camera lens) is often strongly driven by the need to reduce off-axis aberrations in a design that is not inherently spherically symmetrical because of the fact that we require it to have a flat focal surface. The Schmidt camera is a classic example of an imager whose design is based on the principle of spherical symmetry where the powered element is a concentric lens having an aperture stop at its center of curvature providing virtually zero off-axis aberrations. Residual spherical aberration in such a lens can be corrected sufficiently to achieve near-diffraction-limited performance over a very large field of view and by using concentric shells of different glasses excellent spectral bandwidth can be achieved. The resulting design (Figure 9) is much simpler, smaller (40:1), lighter (15:1) and cheaper than a conventional flat-focus lens (see Figure 10 - both lens ~70% of actual) delivering a performance that conventional designs cannot match[24].

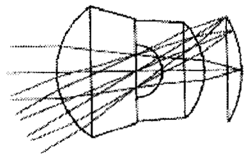

Figure 9. Concentric wide angle lens (60^0 – F/2)

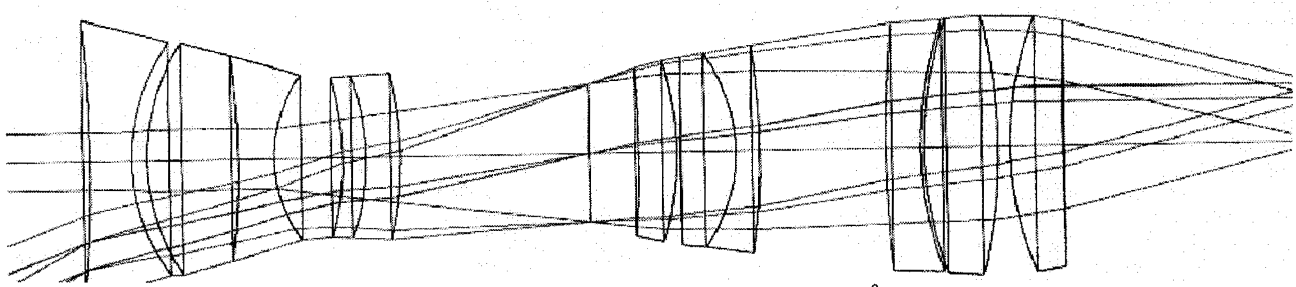

Figure 10. Conventional flat-focus wide angle lens (60^0 – F/2)

Star-tracking satellite navigation systems require a wide field of view and high angular resolution to facilitate concentrating on just the brighter stars to determine pointing direction and ignore the confusing clutter of faint stars. Ultra-wide-angle achromatic concentric spherical lenses have been developed that utilize optical fiber faceplate material to transfer the image from a spherically conforming focal plane to a flat surface in contact with a conventional (flat) detector (Figure 11). Optical fiber faceplate material consists of a fused two-dimensional array of glass fiber waveguides where each fiber must have a solid core that is larger in diameter than the wavelength of imaging light and be surrounded by a cladding of higher refractive index (to channel light through the fiber). To minimize alignment problems these individual fibers need to be much smaller than the pixels in a detector array which diminishes fill factor. The direct losses in fibers and poor fill factor attenuate image intensity to the point that an image intensifier is required.

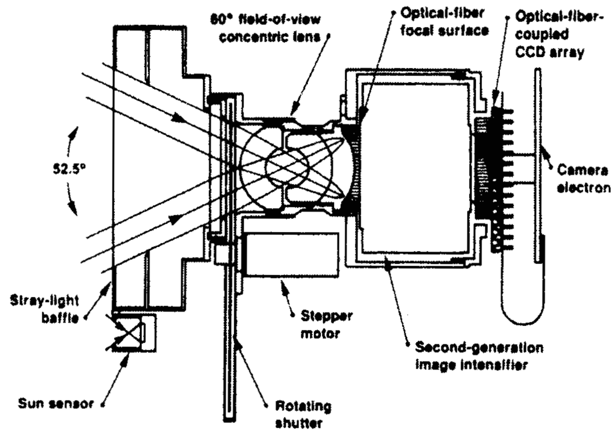

Figure 11. Conventional WFOV Star-Tracking Sensor.

The conventional WFOV star tracking satellite navigation instrument represents a complex and cumbersome means of creating a pseudo curved focal plane which has a resolution that is constrained to be much greater than the wavelength of imaging light. A significant component of this sensor is the fiber optic faceplate which is cumbersome, expensive and suffers from inherent problems such as incomplete fill factor, propensity for broken fibers, nonuniform transmittance, crosstalk, imperfect stacking and need for large pitch imaging arrays.

Curved focal plane imaging sensors suffer from none of these problems enabling a simpler, more elegant, more robust and more compact implementation.

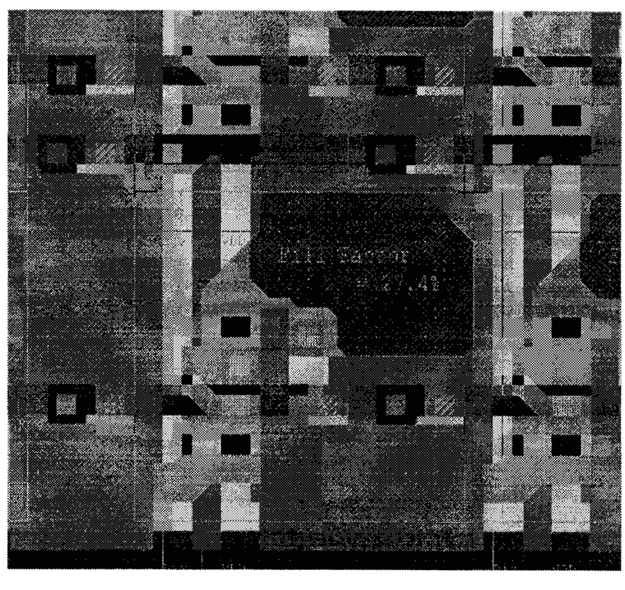

Figure 12. Photogate pixel demonstrating the 27.4% fill factor.

The creation of curved detectors is not currently a popular concept as silicon crystal planes are naturally flat, detector arrays are hard enough to make already, and conventional printing cannot provide sub-micron critical dimensions over the requisite depth-of-field. But, as has been established, the use of curved detectors in image systems greatly simplifies instrument design and enhances instrument performance at a dramatically reduced volume and mass. NASA's need for low power, highly integrated image sensor systems have lead to the development of the CMOS based Active Pixel Sensor (APS) technology. The third generation imager consists of a 512 x 512 photogate array of 12 μm pitch pixels (0.38 mm^2) with a 27% fill factor (Figure 12) designed for 0.6 μm minimum feature design rules. For a curved focal plane version of this APS the sensitive area of the sensor lies on a 0.6 cm x 0.6 cm section of a sphere of radius 6 cm which represents a surface height variation of approximately 300 μm. X-ray printing is an excellent method of patterning a device that departs so strongly from a flat surface. As defined earlier, the resolution which can be obtained in X-ray lithography with a gap of 320 μm and a wavelength of 8Å corresponds to a resolution of 0.25 μm which is more than adequate for patterning 0.6 μm CD masks.

6.2 Spectrometers

Recent developments at JPL have resulted in the fabrication of convex gratings by electron-beam lithography. These gratings are uniquely suited to a particular type of spectrometer design, which can be made very compact and operate at low to moderate spectral resolution, and moderate f-number (> f/2.5). They are also well suited to pushbroom scanning systems, allowing a long slit to be imaged without distortion. However, there is a different class of spectrometric requirements that is not met by that design. It encompasses typically high-resolution spectrometers such as may be required for analysis of atmospheric constituents. These spectrometers generally have a pinhole as input rather than a long slit and require a low f-number for efficient light collection. In addition, good optical correction is critical in reducing the photodetector pixel size and hence overall spectrometer size.

The requirements of this class of spectrometers can be met by a simple design that utilizes only three optical surfaces, one of which is the grating. In this design, the concave fine pitch grating is the largest component. These large gratings are outside the bounds of electron-beam lithographic techniques and holographic techniques are incapable of producing properly blazed grooves. The X-ray technique discussed below is capable not only of providing properly blazed gratings, but also providing variable pitch gratings, or gratings with profile optimized to produce a given spot size. These capabilities enable the design of new types of spectrometers for very high resolution measurements.

The radiation shadow pattern that strikes the surface of substrate is called the areal image of the mask. Generally the lithographic goal is to faithfully define a pattern, not achieve a faithful continuous tone representation of an object (as in microscopy or photography). The modulation transfer function is a measure of the contrast in the areal image and is the ratio of two critical exposure energy densities - the density where the resist will not dissolve in the developer and the density where the resist will completely dissolve in the developer. Clearly as this ratio decreases so does the integrity of the areal image until at a ratio of 0.5 no areal image can be created at all. By working with X-ray integrated dose ranges that provide modulation transfer functions between 0.5 and 1 {which encompass the onset and total solubility of resist in developer (or vice versa for negative working resist)} residual resist densities, after development, will be roughly inversely proportional to the exposure gradient. When the resist matrix is subsequently dried there is a spatial consolidation into a transverse thickness profile for the patterned image.

If a slit aperture is covered with a variable density wedge a groove profile may be produced. Successive translation and exposure of the wedge results in the creation of a triangular or saw tooth blaze grating within resist. Alternatively FIB can be used to machine variable density profiles across a flat X-ray mask and traditional X-ray shadow printing used to provide 'gray scale' exposure of a complete grating. As discussed earlier, the X-ray lithographic technique is capable of maintaining sub-micron feature definition over large variations in feature topography or depths-of-field and electrophoretic photoresist deposition provides uniform thickness conformal coatings over 3-D surfaces. Thus sub-micron defined variable thickness (density) wedge mask will define and laterally control depth by differential exposure with sub-micron precision irrespective of how uneven or irregular the surface.

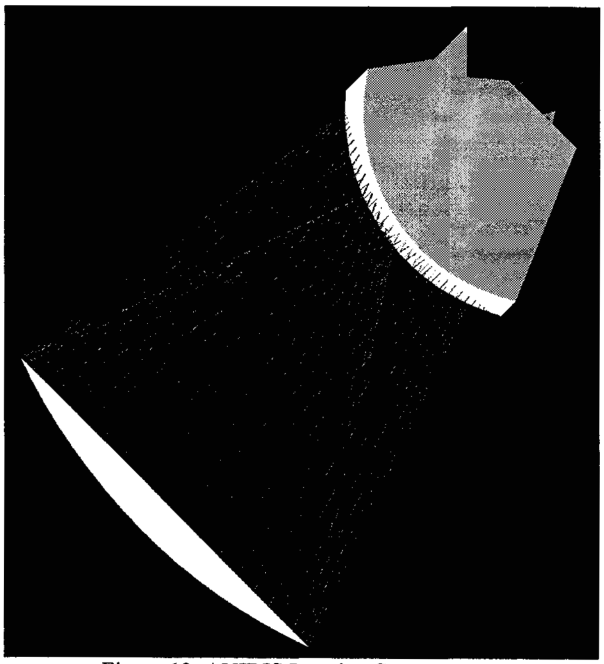

Figure 13. AVIRIS Imaging Spectrometer

The transverse thickness profile of resist may then be covered with reflective metal coating or alternatively the profile negatively transferred into underlying bulk material by reactive ion etching (with resist profile modified to compensate for any differential erosion rate so the post etch surface has the required profile) to realize complex diffractive optics mirror.

Three very simple centered spherical surface designs of optical spectrometers demonstrate the utility of the Blaze gratings. The first design provides ten times the spectral resolution of the current Advanced Visual and IR Imaging Spectrometer (AVIRIS) in about a fifth of the volume. A very low f-number is maintained which provides for a high light gathering capacity. The second design is a miniature spectrometer that can be used for very high spectral resolution measurements, for example, of atmospheric constituents. It gives a spectral resolution of about 0.3 nm, Nyquist-sampled, over the spectral bandwidth of 740-800 nm.

The third design is an imaging spectrometer with a 10 nm spatial sampling and 760 spatial pixels, intended for operation in the solar reflected spectrum. This design achieves extremely low values of spectral and spatial distortion (less than a few percent of a pixel) in addition to providing a very low f-number (~f/1.6 or less - limited by foreoptics arrangement). As such, they rival convex grating designs, by providing higher signal-to-noise ratio due to the improved light collection.

6.3 Nanometer Lithography

In the development of curved focal plane imagers traditional 0.6 µm design rule devices were considered and the large depth-of-field attribute of X-ray lithography exploited to transfer patterns to a 6 cm radius of curvature substrate. The second phase of this research is to transfer a Megapixel APS imager developed for 0.35 µm design rules to a 6 cm radius of curvature substrate which can again be accommodated with X-rays of 8Å wavelength. However, the 'grand challenge' is to explore the development of a Megapixel APS imager for 0.035 µm design rules and the production of 35 nm CD X-ray masks to fabricate the device on a curved focal plane. Such a 'camera' would have an active pixel area of 1 mm^2 and, including lens, occupy a volume of 1 mm^3.

The AVIRIS concave Bragg grating already capitalizes on sub-optical resolution masks and depth-of-focus, future efforts will involve the development of more exotic shaped and variable pitch grating profiles. In MEMS applications sub-optical X-ray lithography will be used to reduce the 1 µm design rules of the SUMMiT process and to undertake sub-micron precision high-aspect-ratio patterning of LIGA structures.

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